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Technical Opportunities for International Collaborations by the U.S. Fusion Program

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This report was prepared by a Working Group at the request of the U.S. Department of Energy, Office of Fusion Energy Sciences in 1997. The report addresses technical opportunities for mutually beneficial collaboration between the United States and other international fusion research programs. A number of outstanding opportunities are discussed.

KEY WORDS: Fusion energy; international collaboration.

EXECUTIVE SUMMARY

In response to a charge from the Department of Energy's (DOE's) Office of Fusion Energy Sciences, a working group (hereafter called "the Working Group") was assembled to address technical opportunities for mutually beneficial collaboration between the United States and foreign fusion research programs. The Working Group identified truly outstanding opportunities where U.S. fusion scientists and engineers could join with their foreign counterparts to carry out research which addresses critical goals of the U.S. fusion program. International collaboration, which uses the unique capabilities of fusion facilities worldwide, as well as international theory and modeling programs, offers an avenue for achieving important scientific goals of the fusion program, without near-term investment in expensive new facilities.

Key recommendations of the Working Group are divided into the areas below.

(1) In the area of burning plasma and tokamak performance:
- Discuss with JET Authorities the possibility that the United States could become a major collaborator in the JET experiment, a machine with strong advanced performance capability and the only existing device capable of D-T operation.
- Pursue an active collaboration on the physics of energy confinement and transport barrier formation on the Japanese experiment JT-60U, a flexible tokamak facility with equivalent break-even performance capability.
- Promote international topical collaborations in the areas of size scaling, power and particle control and long pulse operation.

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(2) In the area of innovative concept developments:
- Establish a strong program of international collaborations on spherical tori, including participation on the National Spherical Torus Experiment in the United States.
- Pursue opportunities for collaboration on stellarators through the Large Helical Device in Japan (with its qualitatively larger plasma volume, heating power, and pulse length) and the Wendelstein program in Germany.
- Expand international collaborations in Inertial Fusion Energy (IFE) and explore the incorporation of IFE issues into the existing fusion energy activities at the International Energy Agency.

(3) In the area of fusion technology:
- Deploy U.S. technologies on foreign experiments to access test conditions unavailable domestically, particularly on scientific issues related to long pulse/steady state operation, high power densities, and reliability.
- Conduct joint development work on the key feasibility issues for fusion technologies and materials, such as neutron irradiation effects, using unique foreign facilities.

The Working Group recognizes the continuing opportunities from international personnel exchanges and from participation in joint experimental and theoretical research in a wide range of areas. The Working Group endorses the promotion of expert groups on key scientific and technology issues facing fusion, building on the ITER Physics Expert Groups and other less formal international groups.

I. INTRODUCTION

This report responds to a request from the Department of Energy's (DOE) Office of Fusion Energy Sciences (OFES) for the U.S. fusion community "to explore the technical options for collaborative activities" [outside of ITER] with foreign research programs on topics of mutual interest. (The charge letter is attached as Appendix I.) This report is intended to form the technical basis for the U.S.D.O.E. to respond to a request from the U.S. House of Representatives' Science Committee for information on international collaborations outside of the International Thermonuclear Experimental Reactor (ITER).

To perform this task, an ad hoc Working Group on international collaborations was established under the leadership of the Princeton Plasma Physics Laboratory, with membership solicited to provide a breadth of programmatic perspectives and access to institutional knowledge bases; the university community was represented through the University Fusion Association. The Working Group conducted its work in a top-down manner; it started with the missions and goals of the U.S. fusion program and used guiding principles and information on foreign programs to identify compelling strategic opportunities for achieving high priority goals by U.S. participation in international research programs. As background, the Working Group used programmatic descriptions of the foreign programs provided by their own authorities and considered summaries of ongoing U.S. international collaborations.

From its inception in the 1950s, the magnetic fusion energy research and development program has been international in character. The U.S. has been a leader in establishing and fostering collaborations that have involved scientific exchanges and joint work on both the U.S. and foreign facilities. In many cases, the U.S. developed and provided specific hardware or diagnostics to conduct experiments on unique fusion facilities abroad, and Japan and Europe made significant investments in several U.S. facilities to carry out their programs. Theoretical studies and computer models have been major elements of these collaborative experiments in both directions. The "voluntary" ITER physics R&D program, coordinated by the ITER Physics Expert Groups, has provided for a closer coordination of a focused world tokamak research program. These collaborations have contributed to cross-fertilization of ideas, expansion of the fusion database, and cost sharing of experiments and hardware in the world-wide pursuit of fusion. Similarly, the inertial fusion energy program has been international since its inception in 1976. Increased international collaboration in inertial confinement fusion is expected because of the recent (almost complete) declassification of the field.

In the past 3 years, the U.S. fusion program budget has been reduced by about 40% and the largest U.S. experiment, the Tokamak Fusion Test Reactor (TFTR) at PPPL, was shut down in April 1997. The United States is left with only two medium-size fusion facilities, DIII-D at General Atomics and C-MOD at MIT, in contrast to Europe and Japan where there are many more powerful, unique, and larger facilities. In addition, Europe, Japan, and Korea are designing and building even more advanced fusion facilities aimed at the scientific and technological frontiers of fusion. The United States and the world fusion community would greatly benefit from an expansion of international collaborations in order to maintain the momentum of scientific developments in fusion at a time when the U.S. resources have been reduced. Furthermore, some of the recent scientific advances in the U.S. program are ripe for further exploitation on unique foreign facilities.

The Working Group was asked to consider whether this compilation of strategic opportunities is sensitive to the range of possible decisions on the future of the ITER project. The Working Group concluded that, in scientific areas of research, the opportunities are technically insensitive to the ITER future, because experimental research on ITER itself would not commence for over a decade, whereas the strategic opportunities represent compelling opportunities for U.S. research in the next 3 to 5 years. In technology areas, if the ITER project were not to proceed beyond the currently agreed upon period of the Engineering Design Activities, the compilation of opportunities contained in this report would have to be expanded to include many generic technology activities now being conducted under the ITER Technology R&D Program.

II. GOALS OF THE U.S. INTERNATIONAL COLLABORATIONS PROGRAM

The international component of the U.S. fusion program should be viewed within the context of the integrated program. The goals of the U.S. international program must be derived from the overall U.S. fusion program goals based on a set of guiding principles.

In January 1996, the Fusion Energy Advisory Committee (FEAC) responded to a charge from DOE's Office of Energy Research (ER) and recommended restructuring the U.S. fusion program "in the light of congressional guidance and budgetary realities." In its report, entitled "A Restructured Fusion Energy Sciences Program," the FEAC recommended that the U.S. fusion program mission be "to advance plasma science, fusion science and fusion technology—which constitute the knowledge base needed for an economically and environmentally attractive fusion energy source." FEAC also recommended three policy goals:

- to advance plasma science in pursuit of national science and technology goals,
- to develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program, and
- to pursue fusion energy science and technology as a partner in the international effort.

These goals were embodied in the DOE Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program (August 1996), as the means for achieving the program's mission:

> Advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.

On September 30, 1997, the Panel on Federal Energy R&D of the President's Committee of Advisors on Science and Technology (PCAST) issued the Executive Summary of its report entitled "Federal Energy Research and Development for the Challenges of the Twenty-First Century." In this report, it was recommended that "The objective of DOE's fusion energy sciences program is to develop the scientific and technological basis for fusion as a long-term energy option for the United States and the world." The Panel reaffirmed support for "the specific elements of the 1995 PCAST recommendation that the program's budget-constrained strategy be around three key principles: (1) a strong domestic core program in plasma science and fusion technology; (2) a collaboratively funded international fusion experiment focused on the key next-step scientific issue of ignition and moderately sustained burn; and (3) participation in an international program to develop practical low-activation materials for fusion energy systems." Regarding international collaborations outside ITER, the Panel observed that "the U.S. program should establish significant collaborations with both the JET program in Europe and the JT-60U program in Japan. Such collaboration should provide experience in experiments that are prototypes for a burning plasma machine, such as ITER, and that can explore driven burning plasma discharges."

III. SITUATION ANALYSIS

Most of the world's fusion research is funded by the European Union (EU) and the governments of Japan (JA), the Russian Federation (RF), and the United States. Smaller, but increasingly significant fusion programs are funded by Canada, China, India, and the Republic of Korea. Other countries funding fusion research activities include Australia, Argentina, Brazil, the Czech Republic, Egypt, Ukraine, Kazakhstan, Mexico, Poland, and Turkey.

The yearly funding for U.S. fusion program was reduced 40% between fiscal years 1995 and 1997. Between fiscal years 1977 and 1998, the U.S. fusion budget was reduced 70% in real terms. In contrast, funding for the EU and the Japanese fusion programs has significantly increased during that same period. In fiscal year 1997, the EU spent nearly three times the amount spent by the United States for fusion research, and we estimate that the Japanese program spent about twice as much as the United States. The defense-related inertial confinement fusion efforts are not included in these numbers, except for the small inertial fusion energy program.

A consequence of the continuous reduction in the U.S. fusion budget has been the inability of the U.S. fusion program to make investments in major new experimental facilities. In contrast, the EU and Japan have continued to design and build new fusion experiments.

In 1995, the Congress instructed the DOE to restructure the U.S. fusion program to be consistent with the expectation that budgets will remain flat for the foreseeable future. Thus, the United States is no longer pursuing fusion as a goal-oriented energy technology development program. A new strategic plan for the fusion energy sciences program was developed, with new program goals that support plasma science research, emphasize the importance of exploring innovative solutions to technical issues, reinvigorate the search for alternative concepts to the tokamak, and recognize the need to pursue research on the scientific and technological foundations for economically and environmentally attractive fusion energy power plants through international collaboration.

Taken together, the reduced budget and the restructuring of the program have resulted in an increasing U.S. need to participate in international collaborations to achieve our fusion goals cost-effectively, to help maintain technical breadth in the program, and to provide access to expensive capital facilities that we are not able to afford.

With energy situations perceived differently than in the United States, the EU and Japan are continuing their goal-oriented fusion energy development programs. The long-term goal of these programs is to produce a prototype fusion power plant. The strategy of both programs includes designing, building, and operating the following systems:

1. An engineering test reactor, aimed at controlled ignition and long-burn of D-T plasmas that will demonstrate the scientific and technological feasibility of fusion power production as well as its safety and environmental potential. This role will be filled by ITER; and
2. A demonstration power plant capable of producing significant quantities of electricity that will confirm the economic feasibility of electricity production from fusion energy.

Although both the EU and the Japanese programs are pursuing the tokamak as the basis for the engineering test reactor, they are pursuing alternative concepts to the tokamak for possible use as the demonstration power plant. Appendix II contains a brief description of the EU, JA, and RF programs. Appendix III summarizes the frameworks and agreements for the current international collaborations.

IV. GUIDING PRINCIPLES

In this section, we identify general principles that have guided the development of strategic opportunities discussed in the next section. Although, some of these points are developed and further discussed in other sections, we summarize them here to provide a useful set of guiding principles for use in the further implementation of U.S. participation in international collaboration on fusion energy and science.

- The development of fusion as a practical energy source is motivated by global energy and environmental issues, as well as national concerns regarding energy security and economic competitiveness. Thus, international considerations are a fundamental part of the overall rationale for fusion energy development.
- The development of fusion energy is a tremendous technical challenge involving substantial commitments of resources, with the commercialization phase decades in the future. Thus, international collaboration to bring together the best worldwide intellectual and facility capabilities is clearly warranted.
- International collaborative efforts are a necessary, integral part of the U.S. Fusion Energy Sciences Program and contribute directly. Such efforts have been a part of the U.S. program since its early days and they are a part of essentially every component of the program today.
- International collaboration, taken as a whole, should allow each participant to fulfill its own objectives. For the United States, international activities should be supportive of the strategy of our Fusion Energy Sciences Program. We, in turn, should understand the needs of our partners.
- The development of effective and productive international collaborations is based on mutual understanding and trust developed over long periods of time. The most productive collaborations occur when all parties “bring something to the table.” For example, successful collaborations by U.S. scientists on foreign devices often include contributions of hardware as well as people. Such

relationships are facilitated by stable national commitments and funding.

- International collaborative activities have covered many topical areas (plasma theory and experiments, technology development, materials research and design studies) and used a wide variety of methods (personnel exchanges, workshops, joint experiments, common planning, etc.). This breadth is an advantage and should be maintained.
- The most comprehensive and ambitious international activity is the International Thermonuclear Experimental Reactor (ITER) Project. Other activities should complement ITER activities and take advantage of the experience gained through the ITER process.
- In light of the strategic goals of the U.S. program and realistic projections of U.S. resources, the U.S. strategy for international collaboration should give priority to those areas where such collaborations are judged essential to meet our goals. We recognize that with present resources it is not possible to have a stand-alone U.S. program. We should identify and pursue those areas wherein the United States could make its largest contributions, in both leading and supporting roles.
- The application of state-of-art information technologies will greatly facilitate future international collaborations through the expanded use of remote operations, transmission and storage of data, telecommunications, electronic communication, etc. In fact, scientific international collaboration, such as fusion research, can be expected to help drive future developments in information technology.

V. STRATEGIC OPPORTUNITIES

Historically the fusion program has been a model for international collaborations, with personnel exchanges and active collaborations even during times of diplomatic conflict. These collaborations and interchanges have been both long term and short term and have covered a wide breadth of topics. To maximize the benefit to the U.S. fusion program, we should continue to pursue a broad-based program of international collaborations, linked to a strong domestic program. From individual investigator interchanges to groups responsible for program elements in foreign programs, an international collaborative program is critical for progress in fusion.

Theoretical and computational investigations of stability, transport, and dynamic behavior of a magnetized plasma have played an increasingly important role in interpreting experimental observations and in developing new ideas for achieving higher performance in both tokamaks and alternate confinement experiments. Even in the area of turbulence-induced energy transport, first principles computations of plasma transport based on 3-D simulations of fluctuations are now taken seriously as predictors of confinement in both present and future experiments. Collaborations among theorists worldwide are ongoing, for example, in the area of tokamak divertor and edge physics and stellarator theory. Such collaborations should continue and be fostered. Detailed comparisons between experimental observations and theoretical predictions have become an important tool in validating models. The broad range of experiments that are supported in the international fusion effort therefore also become a valuable resource for the U.S. theory program. Collaborations between the U.S. theory program and experimental programs outside of the United States should be encouraged.

An important success of the ITER collaboration has been the formation of expert groups on key physics topics. These groups have been effective in rallying experimentalists worldwide to carry out critical physics experiments focused on issues affecting the design of an energy producing plasma experiment. The resultant pooling of information from the tokamak experiments worldwide has promoted the rapid advancement of the scientific knowledge base. The Working Group recommends that the United States propose to the international community that expert groups on key scientific and technology issues be promoted, regardless of decisions about the future of ITER. As in the present ITER Expert Groups, the expert groups should act as catalysts in the international fusion community for addressing scientific issues.

The Working Group recognizes the existence of continuing opportunities with international personnel exchanges and with participation in joint experimental and theoretical research in a wide range of areas.

The following three sections elaborate on specific high-impact areas for U.S. participation in other fusion programs worldwide.

Strategic Opportunities in Burning Plasma and Tokamak Performance

The tokamak is presently the most advanced energy containment configuration being pursued by the magnetic fusion energy sciences program. Worldwide there are a number of ongoing tokamak experiments with a wide variety of designs and capabilities. The largest facilities are the JET in Europe, which can operate with a deuterium/tritium (D-T) mixture to produce energy, and the JT-60U in Japan, which has performance capabilities comparable to JET but without tritium. With the shutdown of the TFTR facility, the United States has no fusion experiment that is capable of energy production or is comparable in size or performance to these experiments. International collaboration which makes use of the unique capabilities of fusion research devices worldwide, especially JET and JT-60U, offers an avenue for achieving important scientific goals of the fusion program without investment in expensive new facilities in the near term.

One of the rationales for such major collaborations is grounded in the important new experimental results on tokamak confinement of the past several years which have raised the prospects that JET may be capable of operation in a strong self heating regime; that is, where local heating due to energetic alpha particles produced during fusion of D-T is comparable to that due to external sources. Energy containment in tokamaks and other configurations has been a major factor controlling the size of experiments required to achieve ignition or near ignition conditions in laboratory experiments. It has been known that the leakage of energy out of the experimental devices is a consequence of small scale turbulence. The control of this turbulence through the formation of transport barriers, first in the plasma edge (H-mode) and more recently in the plasma core in experiments on TFTR, DIII-D, PBX-M, JET, JT-60U and C-MOD have culminated in recent DIII-D experiments in which the turbulence was sufficiently reduced throughout the entire plasma that it was no longer the primary factor controlling energy leakage by the ions.

The underlying physical processes controlling the formation of transport barriers are not yet sufficiently well understood to know with certainty whether they can be used in reactor-like conditions. In addition, the loss of energy through the electrons continues to be driven by small scale turbulence. A scientific goal of the JET and JT-60U collaborations would be to complement the ongoing DIII-D and C-MOD experimental programs in trying to understand and control these physical processes and, in particular, their robustness under strong self-heating conditions and their accessibility in machines closer to the physical size required to achieve ignition.

These collaborations will also provide valuable scientific information critical to the design and performance projection of the proposed ITER experiment and to possible cost reduction opportunities. We should use the delay in the ITER construction decision as an opportunity to consolidate the ITER physics basis.

Burning Plasma and Advanced Tokamak Collaboration on the JET Experiment

One of the major recommendations in the 1996 FEAC advisory report, "A Restructured Fusion Energy Sciences Program," was to burning plasmas; that is, plasmas that produce significant energy internally through D-T reactions. With the shut-down of the TFTR experiment at Princeton, the United States has no facility capable of D-T operation and participation in the burning plasma experiments in the proposed ITER device are, at best, more than a decade away. To pursue this leg of the FEAC recommendations, the Working Group recommends that the DOE discuss with JET authorities the possibility that the United States could become a major collaborator in the JET experiment, the only existing device worldwide capable of D-T operation.

Steady-state transport barriers, if they could be achieved on the JET experiment, could lead to enhanced performance and operation in the scientifically important regime where self-heating due to D-T reactions is comparable to the input energy. These JET experiments would explore important burning plasma issues such as the stability and robustness of transport barriers in plasmas in the self-heating regime, the impact of energetic alpha particles on stability and energy containment, control of alpha particle energy deposition (channeling), and the buildup of ash. The use of an existing facility for these experiments will be far and away the least expensive option for pursuing our science objectives in this area.

The Working Group recognizes that a successful collaboration will require careful discussions with JET authorities to identify joint interests. The Working Group further recognizes that we cannot unilaterally present a detailed plan for the joint program. Nevertheless, the Working Group recommends that the collaboration include not only the support for scientists and engineers, both at the JET site and possibly at remote sites, but also the fabrication and delivery of hardware to the experimental site, as appropriate. The United States could potentially contribute hardware in the areas of auxiliary heating, in the form of additional neutral beams or more efficient antennas for radio frequency (ICRF) heating, and diagnostics. Successful remote research on the JET machine from the United States would demonstrate a compelling capability for future operation of ITER or other large-scale international experimental collaborations.

Advanced Tokamak Collaboration on the JT-60U Experiment

The formation of transport barriers in tokamak plasmas has fundamentally altered our understanding of energy containment in fusion experiments: Energy confinement in experiments can be manipulated. These control techniques may lead to much more compact designs for experiments on energy-producing plasmas, reducing the overall cost of the development of practical fusion power. There are, however, still significant gaps in the understanding of how these barriers form, their stability, and whether they can persist for sufficient time in an energy producing environment. In the DIII-D experiment, it was demonstrated that turbulence driven ion transport could be suppressed throughout the entire plasma, leading to greatly improved confinement of the plasma energy. In the larger plasmas required for an energy-producing plasma experiment, however, it is not known whether the formation of global transport barriers is possible and, therefore, whether they can be relied upon in the design of future experiments. Because of the significant size difference between the existing U.S. tokamak facilities (DIII-D and C-MOD) and JT-60U, a comparison of experimental observations of barrier formation and confinement properties of the various machines can resolve some of these uncertainties. In addition, the JT-60U experiment has a very flexible design which allows the exploration of plasma shape on energy containment. The Working Group, therefore, recommends that the United States pursue an active collaboration on JT-60U concerning the physics of energy confinement and transport barrier formation.

The JT-60U experimental program has already made very significant contributions to the physics of transport barriers in the high pressure regimes relevant to burning plasma experiments. In addition, it has demonstrated that plasma shape impacts confinement and that the barriers can be sustained for a substantial fraction of the plasma lifetime in the experiments. Developing techniques to control the location of transport barriers through localized heating and extending their lifetime by driving current with noninductive techniques should be part of the collaboration. An active collaboration between DIII-D and JT-60U on the influence of plasma shape on confinement is already in place and should continue. The diagnostic techniques developed for the U.S. experiments have played an important role in the development of theoretical models of energy containment. Their implementation on JT-60U would be a critical element in trying to establish the physics basis of confinement in JT-60U experiments.

International Topical Collaborations in Tokamak Physics

The wide variety of designs and capabilities of tokamak experiments worldwide is an important resource for addressing key scientific and technology issues facing fusion. The pooling of information from these experiments during the ITER project has promoted the rapid advancement of the scientific knowledge base. The Working Group recommends that the United States propose to the international community that International Topical Collaborations on key scientific and technology issues be established. These topical collaborations typically would involve multiple experiments worldwide and should act as catalysts in the international fusion community for addressing key scientific issues. Examples are the scaling of energy confinement with machine size, the design of divertors for suppression of impurities and the efficient removal of ash, and the control of plasma dynamics during steady-state operation.

Size Scaling

A Topical Collaboration on size scaling would organize experiments worldwide to compare energy confinement in plasmas with similar dimensionless parameters (pressure, collisionality, etc.) in large, medium, and small machines. Considerable work has already been done in this area, leading to empirical scaling relations based on engineering parameters or dimensionless physics parameters. However, the multiplicity of parameters and the fact that these experiments tend to be done independently has tended to obscure the size dependence. A focused and coordinated campaign on a select group of the world's tokamaks could provide a significant advance in our understanding of size scaling. Relevant tokamaks might be TCV, JFT-2M, C-MOD, DIII-D, Asdex-Upgrade, JET, and JT-60U or some subset of these. Ongoing collaborations on size scaling include DIII-D, C-MOD, Asdex-Upgrade, and JET. These efforts should be expanded and include other machines, especially JT-60U.

Other important scientific issues in tokamak physics may also depend critically on plasma size and the scaling with size must therefore be understood in designing future ignition experiments. Examples are the scaling of the H-mode power threshold, the time scale for current quenching during disruptions, and stability of toroidal Alfvén eigenmodes.

Power and Particle Control

The development of divertors to bridge the transition from the high temperature core plasma to the cold material wall of a plasma confinement experiment has been a major scientific goal of the fusion program. Divertors have two primary functions: to reduce the heat flux from the hot plasma core to the material surfaces of the vessel wall, and to control the influx of impurities and neutral gas back into the main plasma. Both of these goals must be accomplished without degrading good H-mode confinement and in particular the edge transport barrier. The achievement of effective divertor operation becomes increasingly difficult with larger power flux from the plasma core to the edge. Thus, the divertor becomes a critical component in projecting the performance of future ignition experiments. As a result of the ITER EDA, the international community has been engaged in a vigorous collaboration on divertor design and particle control techniques. Programs which have been active in this area include DIII-D, C-MOD, Asdex-Upgrade, TEXTOR, and JET. Active collaboration in this area should be continued.

Long Pulse

The development of an attractive tokamak fusion energy source will, at minimum, require very-long-pulse operation. Although the self-generated (bootstrap) currents can provide most of the current in a tokamak, long-pulse operation will ultimately require radiofrequency or neutral beam techniques for driving current. In addition, transport barriers have been studied as transient phenomena in a variety of machines. The implementation of such techniques in an energy producing plasma experiment will require the development of techniques for maintaining and controlling barriers under steady-state conditions. Although some of these issues can be addressed within the U.S. fusion program and the JET and JT-60U experiments, because of their long pulse lengths, the Tore Supra experiment in France and the future KSTAR experiment in Korea can best address these issues. An international focus on the issue through a Topical Collaboration would aid in focusing the international scientific community.

There are two fundamental time scales which naturally arise in addressing long-pulse tokamak operation. The first is associated with the plasma relaxation time and the wall skin time. The second is the plasma-wall equilibration time. In large tokamaks, the first time scale is usually on the order of several seconds, whereas the second time scale is on the order of 100 to 1000 seconds. Issues related to the first time scale can be addressed by many tokamaks, including DIII-D and C-MOD in the United States. The French superconducting tokamak Tore Supra is presently the only large tokamak in the world that is specifically designed to address long-pulse operation. So far, improved confinement in pulse length up to 120 seconds has been achieved. The upgrades presently under construction (CIEL project) are aimed at 1000-second pulse length and will be operational after the year 2000. Tore Supra is well-suited for studies of advanced radiofrequency control techniques because of the availability of power in a variety of frequency regimes, long-pulse capabilities, unique fast electron diagnostics, and the ability of the experiment to access high-performance operating regimes. The U.S. Fusion program is already involved in collaborations with the Tore Supra Program and, because of the unique opportunities in developing long-pulse operation, this topical collaboration should be continued.

The Korean Superconducting Tokamak Research device (KSTAR) will also have long-pulse capabilities similar to Tore Supra, but with a noncircular cross-section and a poloidal divertor. KSTAR is presently under conceptual design and is planned to begin operation in mid 2002. This device is similar to the U.S.-proposed Tokamak Physics Experiment (TPX) and has the potential to make a major contribution to the worldwide understanding of steady-state processes in fusion reactors. The United States should participate in an active way in this fusion research program.

Recommendations:

- Discuss with JET authorities the possibility that the United States become a major collaborator in the JET experiment, a machine with strong advanced performance capability and the only existing device capable of D-T operation.
- Pursue an active collaboration on the physics of energy confinement and transport barrier formation on the Japanese experiment JT-60U, a flexible tokamak facility with equivalent break-even performance capability.
- Promote international topical collaborations in the areas of size scaling, power and particle control, and long-pulse operation.

Strategic Opportunities for Innovative Concept Development

The development of innovative concepts has become an important part of the U.S. fusion program strategy. Several of the innovative concepts under investigation within the United States are being aggressively pursued by other nations, which have invested in large facilities aimed at extending plasma performance beyond what can be achieved in U.S. facilities. Collaboration with these foreign programs would allow us to assess the viability, influence the development, and test ideas for further improvement of these concepts. In addition, our experience in developing tokamaks indicates that our domestic efforts benefit greatly from the exchange of ideas and the scientific competition engendered by international collaborations.

The U.S. program does not, by itself, have the resources to bring any innovative concept from initial conception to its ultimate embodiment as a fusion power reactor. Hence, U.S. participation in the ultimate development of any innovative concept will depend both on positive results from that concept's development program and on the formation of international partnerships to complete proof-of-performance and D-T burning experiments. Some innovative concepts already have broad international support (e.g., stellarators, spherical tori, RFPs). In these areas, an important goal of U.S. collaborations should be to maximize the scientific benefit to the U.S. program, and to begin building the scientific and technical partnerships which will be required for the U.S. program to participate in carrying these concepts toward their reactor embodiment. In other areas (e.g., spheromaks, FRCs, magnetic dipoles), the international effort is small. Positive results from U.S. efforts to develop these concepts should be used to interest prospective international partners in joining us in the further development of these concepts.

Areas in which there are particular opportunities for international collaboration include spherical tori (STs), stellarators, and inertial fusion energy (IFE).

Spherical Tori

Spherical Tori (ST) provide the United States with a strategic opportunity to be an international leader in the development of this promising innovative concept. The success of the present generation of ST experiments, including START in the United Kingdom, the HIT-II and CDX-U experiments in the United States, and the TST-M experiment in Japan, has motivated the construction of a new generation of 1-MA-class ST experiments, including the National Spherical Torus Experiment (NSTX) in the United States, the MAST experiment in the United Kingdom, the GLOBUS-M experiment in Russia, the ETE in Brazil, and the PEGASUS experiment in the United States. The key scientific issues to be addressed with this new generation of ST experiments are the exploration of beta-limits and energy confinement and the development of reliable means for generating and sustaining the plasma current while dissipating little (or no) poloidal magnetic flux. The United States has been an active collaborator in the international ST program to date (e.g., by supplying the neutral beam system which allowed the START experiment to reach a record toroidal beta of 33%). With the construction of the National Spherical Torus Experiment, the United States is proceeding actively in this area.

Stellarators (Helical Systems)

An important opportunity is presented by the foreign stellarator program where billion-dollar-class facilities are under construction: the near-term (March 1998) Large Helical Device (LHD) in Japan and the later (2005) Wendelstein 7-X (W7-X) in Germany. These are supplemented by more moderate-size ($50 million to 100 million scale) research facilities presently in operation in Japan (Compact Helical System and Heliotron E), Germany (Wendelstein 7-AS), Spain (TJ-II), etc. LHD will allow study of stellarator physics at more reactor-relevant parameters (beta $\geq$ 5%, ion temperature $\sim$ 10 keV, energy confinement times of hundreds of ms, etc.) The order of magnitude increases in plasma volume, heating power, and pulse length of LHD over that in existing stellarator facilities will allow size scaling studies for a confinement concept that is second only to the tokamak in development. The superconducting coil system, divertor, and steady-state multi-MW heating power allow comparison with steady-state component development in tokamaks (particularly Tore Supra).

Both LHD and W7-AS can provide tests of physics and optimization principles needed for stellarator development in the United States aimed at a more compact, high-beta disruption-free reactor concept. An additional benefit is the broadening of our understanding of toroidal confinement (e.g., steady-state transport barriers) through comparisons with related tokamak issues. Areas of particular importance are ion heating, neoclassical transport, the role of electric fields in confinement improvement, enhanced confinement modes, beta limits, particle and power handling, and profile and configuration optimizations. The wide range of stellarator configurations accessible on LHD, W7-AS, CHS and TJ-II allow study of the role of aspect ratio, helical axis excursion, magnetic-island-based divertors, and the consequences of a net plasma current, elements that are being incorporated in low-aspect-ratio stellarator concepts under consideration in the U.S. program.

Inertial Fusion Energy

The United States would also benefit by collaboration with Japan and Germany in the IFE area. Collaboration on development of direct-drive laser-driven IFE (including fast ignition) and reaction chamber R&D should be pursued with the Institute for Laser Engineering at Osaka University, Japan, through the U.S.-Japan bilateral agreement on fusion. Another important opportunity is an inter-laboratory cooperation on dense plasma physics and heavy-ion fusion target physics with the Gesellschaft für Schwerionenforschung, a large heavy-ion accelerator laboratory in Darmstadt, Germany. This collaboration is exploring induction bunching in order to shorten ion pulses from storage rings to increase peak ion beam power at the target, adiabatic plasma lenses, and plasma channel focusing. Also, it could explore the addition of an auxiliary short pulse laser to preheat solid radiator targets with hot electrons. These would enhance future driver designs and allow dense plasma physics experiments relevant to heavy-ion fusion targets to be performed at this time.

Recommendations:

- Establish a program of international collaborations on spherical tori, including international participation on the National Spherical Torus Experiment in the United States.
- Pursue opportunities for collaboration on stellarators through the Large Helical Device in Japan (with its qualitatively larger plasma volume, heating power, and pulse length) and the Wendelstein program in Germany.
- Expand international collaborations in Inertial Fusion Energy (IFE), and explore the incorporation of IFE issues into the existing fusion energy activities at the International Energy Agency.

Strategic Opportunities in Fusion Technology

The goals of the U.S. Fusion Technology program are to demonstrate marked progress in the scientific understanding and development of the advanced technologies and materials required to withstand high plasma heat and particle fluxes and neutron wall load environments, and to develop the enabling technologies required to create, control, and understand the plasma state in existing or near-term tokamaks and in alternate concepts. Research in these areas is critical to the evaluation of the potential attractiveness of fusion as an energy source. International collaboration on fusion technology research will enhance progress of the U.S. program by cost sharing of the more complex and expensive experiments, and by providing access to non-U.S. test facilities. We will also gain access to foreign technology and results from such collaborations. Innovation will be stimulated by the need to meet a wide variety of requirements on a range of fusion concepts, not all of which can be investigated by the United States.

Technology collaborations have historically been carried out under bilateral agreements either between parties, e.g., the U.S.-Japan Fusion Cooperation Program, or between the United States and a particular machine, e.g., the United States and Tore Supra. Other collaborations have been carried out under various multinational agreements, such as the IEA and IAEA, particularly in the materials area. Many of these collaborations were reduced in scope when the U.S. Base Technology Program was severely curtailed in FY96. Collaborations aimed at technology development for specific applications (e.g., pellet fueling, RF heating, plasma facing component development) existed with JET, JT-60U, Tore Supra, TEXTOR, and ASDEX. In addition, advanced technology and materials research were conducted through bilateral collaborations with Japan through JAERI and the Ministry of Education, with several European laboratories and with the Russian Federation. The United States should maintain its participation in working groups that are planning and coordinating such efforts.

In the United States, most technology development is now carried out in support of the ITER Engineering Design Activities (EDA). The principal focus is on superconducting magnet development and R&D related to divertor and first wall issues. Other activities include safety research, plasma fueling and heating, tritium processing systems, remote welding and cutting, and metrology systems. Some of this activity will continue after the EDA but more emphasis is expected on a broader range of issues in the Base Technology Program.

The development of fusion energy will require long-pulse or steady-state operation. The primary issues for the enabling technology development are in the power density and long pulse arena. This activity complements the opportunities discussed previously. Presently, the French superconducting tokamak Tore Supra is the only operating large machine in the world designed for long-pulse operation with high power density. It has fully water-cooled, steady-state, plasma-facing components for power and particle control as well as steady-state wave heating and pellet fueling techniques. A multilaboratory collaboration of the United States with the French program has given the former its first hands-on experience with the challenges of steady-state plasma operation. This is one example in which the investment of relatively modest resources can be leveraged to result in U.S. machine time and hands-on experience with a major foreign device. Substantial opportunities continue to exist to participate in the long-pulse plasma facing component, plasma fueling, and plasma heating programs on Tore Supra. Other opportunities for long-pulse technology development are on LHD and also on W7-X now under construction. Another area of importance for long pulse operation is the development of superconducting magnets, in which the United States should continue to participate.

International collaboration on the enabling technologies should include: superconducting magnets, plasma facing materials and components, plasma material interactions, wall conditioning and particle control, plasma fueling and fuel process systems, and plasma heating systems. The most likely devices for such collaborations include Tore Supra, LHD, ASDEX-U, TEXTOR, JET, JT-60U, and KSTAR. We should enlarge the scope of the existing bilateral technology exchanges with Japan, Russia, and Europe in these areas.

Development of fusion technologies and materials is critical to both the economic and the safety/environmental features of fusion. This will be even more important for advanced high-power density machines envisioned with improved plasma physics. The identification and evaluation of high-performance concepts with high-neutron wall load capability, high-power density components, and attractive safety and environmental features is essential for progress on fusion energy. This involves performing research on innovative high-performance concepts with large potential payoff. The development of low activation materials is an important part of this effort. Progress requires advancing the sciences necessary for understanding and evaluating the performance and interactions of an attractive and compatible combination of low activation structural, breeding, cooling, and plasma facing materials. Effects of irradiation on materials or components must be conducted in the limited number of fission reactors available in the international community until a high flux 14-MeV neutron source is constructed.

For the longer term, international collaboration on fusion technologies and materials should include: Breeding Blanket and Shield Systems; Structural Materials and Radiation Effects; Remote Maintenance and Reliability; Systems Analysis and Safety Research; and Instrumentation in the Fusion Environment. We should continue to participate in research on high-performance breeding blankets and joint fission reactor irradiations on advanced materials. The United States should continue to participate in the discussions on an international fusion neutron source.

Recommendations:

- Deploy U.S. technologies on foreign experiments to access test conditions unavailable domestically, particularly on scientific issues related to long-pulse/steady-state operation, high-power densities, and reliability.
- Conduct joint development work on the key feasibility issues for fusion technologies and materials, such as neutron irradiation effects, using unique foreign facilities.

APPENDIX I. CHARGE LETTER

Dr. Robert Goldston
Director
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Dear Dr. Goldston:

We are pleased to have received John Schmidt's letter of April 11, 1997, proposing to help us with our international collaborations planning activities. At our recent meeting, we discussed the House Science Committee request that the Department answer, by February 1998, several questions regarding international collaborations. Part of our response will be to develop a Strategic Plan for International Collaborations on Fusion Science and Technology Research. The development of this strategic plan will require the involvement of researchers from throughout the U.S. fusion community, and thus your offer to help is both timely and in keeping with the intent of the Leesburg discussions about the role of the Princeton Plasma Physics Laboratory in the fusion energy sciences program.

The United States has already established mechanisms for collaborating with international partners in every element of the fusion energy sciences program. The ongoing restructuring of the fusion program and the need to maximize the effectiveness of the resources expended on fusion research by the United States and our partners in this time of constrained spending, make it important that we review the current program and ensure that we have clearly defined missions, goals and strategies to guide our collaborations in the future. Therefore, we endorse your suggestion that the Princeton Plasma Physics Laboratory lead a national Working Group to explore the technical options for collaborative activities with other Parties where our research goals and priorities match.

The process of developing a strategic plan for international collaborations will have at least four steps:

1) the national Working Group will be convened under PPPL auspices to explore technical options.

2) using these technical options, a strategic plan for international collaborations will be drafted by the Office

of Fusion Energy Sciences in consultation with the Working Group

3) the draft plan will be reviewed by the Fusion Energy Sciences Advisory Committee (FESAC) and revised based on the comments received

4) the required executive branch concurrence will be sought and the plan will be transmitted to the Congress.

We estimate that the formal concurrence process will require about two months. We will engage the Office of Science and Technology Policy and the Office of Management and Budget throughout the process to increase the probability of a successful and speedy approval. Our view of a possible schedule for completing this work is enclosed. We would anticipate having a finished product in time to submit it to the Congress along with the fiscal year 1999 budget. This timing will allow us to take some steps in fiscal year 1999 toward initiatives that would begin to receive funding in fiscal year 2000.

With the completion of the strategic plan and its transmittal to the Congress, we, with the continuing assistance of the national Working Group and the fusion community at large, can then proceed to develop a plan for implementing the strategy.

To meet the rather tight schedule contained in the Congressional directive, we suggest that you work with other fusion community leaders to appoint appropriate persons to the National Working Group and arrange for a meeting of that group as soon as possible. At the meeting it will be necessary to discuss roles and responsibilities of participants, deliverables, and the schedule for this important undertaking. We are sending copies of this letter to key fusion program people to let them know that we fully support establishment of this National Working Group.

In the Office of Fusion Energy Sciences, the International Collaborations Team will have the responsibility for the success of this activity. The team is led by Albert Opdenaker (301-903-4927, e-mail: albert.opdenaker@oer.doe.gov), who will be the OFES representative to the Working Group. A1 reports to Michael Roberts, Director, International and Technology Division.

Sincerely,

N. Anne Davies
Associate Director
for Fusion Energy Sciences
Office of Energy Research

APPENDIX II. FOREIGN FUSION PROGRAMS

The European Union's Fusion Program

The EU fusion program is pursuing three major areas simultaneously: Next Step/ITER, concept improvements, and long-term technology. The main tokamak device is the Joint European Torus (JET), which began operations in 1983. Medium-sized tokamaks in Europe include ASDEX-U, FTU, TCV, TEXTOR, and Tore Supra, all currently focused on physics and technology issues important for ITER.

The EU program's tokamak research is complemented by the investigation of concept improvements for fusion power plants. This work focuses on improvement of the tokamak concept, together with the development of the stellarator and the reversed field pinch. Key facilities include MAST, a spherical tokamak now under construction; Wendelstein 7-AS and TJ-II, stellarators now operating; Wendelstein 7-X, a large superconducting stellarator now being constructed; and the RFX, a reversed field pinch.

The long-term technology program in Europe is oriented toward optimizing fusion as an energy source. It includes environmental acceptability, safety, and socioeconomic considerations. Low activation structural materials, tritium breeding blankets, conceptual design activities for a high energy neutron source for the testing of materials, and continuing analysis of safety, environmental and socioeconomic aspects of fusion energy are the major topics explored in this area.

The European fusion program maintains a "watching brief" on inertial confinement fusion approaches that are being pursued in some European countries, the United States, and Japan.

There has been substantial strengthening in recent years of the interaction between the European fusion program and industry, centered mostly on ITER activities.

The Japanese Fusion Program

The Japanese fusion program has strong support in the Diet. There are two organizations of Diet members thaexplicitly support fusion research. The total number of Diet members belonging to these groups is nearly 100, and they represent almost every political party.

The Japanese fusion program includes both magnetic confinement and nonmilitary inertial confinement activities. It focuses on both the tokamak and a broad range of other options with the leading option being the stellarator (called a "helical system" in Japan). Japan has a substantial international collaboration program, mostly with the United States.

The main tokamak device is the JT-60U, at the Japan Atomic Energy Research Institute, which started operation in 1991 following the upgrading of the previous JT-60 device (commissioned in 1985). JT-60U is a 6 MA tokamak, with high additional heating and current drive capabilities and a divertor. Although tritium operation is not planned, its elongated plasma cross-section, poloidal divertor, and high heating power capability make it suitable for a range of ITER-relevant tasks, to which it is now being directed.

Further tokamak activities are carried out on the smaller JFT-2M, operated by JAERI, and devices operated under the Ministry of Education at various universities. Exploration of steady-state operation, although at moderate performance levels, is being undertaken on the superconducting TRIAM-1 M tokamak, which has attained plasma pulse duration of hours. Strong activities are also undertaken in the areas of heating (in particular using neutral beam and electron cyclotron frequency) and current drive systems.

The helical systems program is particularly strong: facilities include the superconducting Large Helical Device (LHD) under construction and the Compact Helical System (CHS) now operating, both at the National Institute for Fusion Science, and also the Heliotron-E at Kyoto University. Studies on compact tori, including reverse field pinch configurations and open-ended confinement systems, are also being undertaken. A nonmilitary inertial confinement fusion program is conducted at Osaka University. The inertial confinement program budget for 1996 was about 2.5% of Japan's total fusion budget.

Industrial participation in fusion R&D in Japan is substantial. The Japanese Federation of Economic Organizations (which involves the major industrial firms in Japan) strongly support fusion in general and ITER in particular. Leading industrial firms, such as Hitachi, Kawasaki, Mitsubishi, NEC and Toshiba, hold a pivotal role in the design and construction of fusion devices. The industrial participation is coordinated through the Japan Atomic Industrial Forum. This strong industrial involvement in fusion R&D has allowed Japan to develop a sound basis for such fusion technologies as superconducting magnets, remote handling, plasma heating, high heat flux component testing, vacuum technology, and the development of blanket and structural materials.

The Russian Federation Fusion Program

The former Soviet Union was a pioneer in fusion research. Early theory and experiments in Russia led to development of the tokamak. The Soviets developed gyrotrons and were in the forefront of radiofrequency heating of plasmas (now widely used). In recent years, the difficult economic situation has affected the Russian effort, but medium-sized tokamaks and a stellarator are in operation.

The Russian fusion program is divided between two federal programs in science and technology:

- ITER Project and supporting R&D, by far the largest part; and
- Thermonuclear research and plasma applications for civilian purposes.

For the ITER portion of the program, the Prime Minister has authorized the RF Ministry of Atomic Energy to sign a possible Extension of the ITER EDA Agreement until the year 2001 and instructed the RF Ministry of Economics and the RF Ministry of Finance to envisage in their budget proposals for the year 1998 the funding of ITER at approximately the 1997 level.

The non-ITER portion of the Russian fusion program includes research and development in many areas: small tokamaks (T-10, T-11, spherical torus Globus, etc.), stellarators, open traps, “plasma focus,” beam devices, inertial fusion, theory and computational physics, diagnostics, conceptual design and small scale R&D in fusion technology for the Russian national DEMO reactor, and plasma applications.

The Korean, Canadian and Chinese Fusion Programs

In addition to the major fusion programs described above, the United States has bilateral fusion research agreements with Canada, China, and the Republic of Korea.

The Republic of Korea, a newcomer to fusion research, is actively seeking international cooperation in the design and construction of a $300 million superconducting tokamak, the Korean Superconducting Advanced Tokamak Research (KSTAR) facility.

Although the future of the Canadian fusion program is in doubt, Canada has developed an outstanding expertise in tritium technology and remote handling and participates in ITER through cooperation with the EU.

The fusion program in China conducts research at several facilities. A superconducting tokamak, HT-7, has been operating since 1994, and China is planning to construct a new superconducting tokamak of a size similar to the KSTAR device in Korea.

Smaller Fusion Programs

There are other fusion programs with which the United States does not have bilateral fusion research agreements. With varying degrees of financial commitment and development, these smaller but significant fusion programs include Australia, Argentina, Brazil, the Czech Republic, Egypt, India, Kazakhstan, Mexico, Poland, Turkey, and Ukraine.

APPENDIX III. THE U.S. FRAMEWORK FOR INTERNATIONAL COLLABORATIONS

There is a wide web of productive linkages among fusion programs worldwide, within which ITER is only one, albeit a very large, element. Most of these linkages involve the United States and many of them have been stimulated in some way by the United States.

The pattern of this web can be drawn as underlying strands of bilateral connections between each of the fusion programs, and as multilateral activities under the auspices of the International Energy Agency (IEA). Additional strands represent interactions under the auspices of both the International Atomic Energy Agency (IAEA) and various professional technical societies, as well as personal relationships among technical personnel. ITER then overlies and adheres to this web, thereby strengthening the overall fabric of international cooperation.

The most recent enhancement to the comprehensiveness of this web has been the accession of the Russian program to those specific IEA-sponsored agreements covering (1) Stellarator R&D, (2) Environment, Safety & Economics Studies, (3) Materials Research, and (4) Fusion Nuclear Technology, and the accession of the Chinese program to the IEA Materials agreement.

In the chronological development of this collaborative framework, bilateral activities were crucial to learning about each other, establishing mutual interests, and practicing cooperation. This important role is being played today in the newly evolving bilaterals with China and Korea. As the bilaterals with the European Union, Japan, and Russia matured, we found that the common interests extended multilaterally as well and the IEA Implementing Agreements were developed. The latest evolution has been the introduction and growth of the ITER Engineering Design Activities in 1992. Tasks most appropriately carried out by ITER are done in that framework under the auspices of the IAEA; tasks of broad interest but not specific to ITER are carried out under IEA auspices; tasks of specific interest to two parties remain under the bilateral auspices. The intense ITER interaction has so improved communication among most program leaders in the ITER parties that bilateral policy meetings are in some cases now typically held as adjuncts to other international meetings, rather than as stand-alone multiday investments.

The Agreements for Fusion

Each of these agreements has its own character, depending on the individual participants, the facilities being used, the history of interaction, and relationship to the underlying domestic program. Each bilateral program has been an increasingly effective mechanism to advance fusion research with both sides committed to carrying out the exchange activities as noted below.

The Bilaterals:

- U.S.-Russia Bilateral: Covers five broad thematic areas, e.g., materials development, encompassing more than 40 specific activities involving over 80 participants; many of these interactions directly coordinate multi-year cooperative tasks. The newest activity is one designed to improve each side's understanding of the other side's personnel safety approaches and procedures applicable to exchanges of personnel and equipment.
- U.S.-Japan Bilateral: Covers six project or program areas, e.g., cooperative experiments on D-III-D, that encompass over 100 specific activities involving over 200 participants; many of these interactions involve joint hardware tasks. The newest activity is an exploration of common interests in inertial fusion energy work.
- U.S.-European Union (EU) Bilateral: Focuses on three topical project and program agreements, e.g., cooperative experiments on Tore Supra (in France), encompassing three specific activities and approximately 70 personnel, also involving joint hardware tasks. The newest activity is an effort to establish an arrangement between the DOE and Italy's ENEA fusion program.

In addition to these principal bilaterals, there are now three other arrangements:

- U.S.-Canada Bilateral: Focuses on technology efforts in a small number of areas, primarily fusion fuel systems, tritium fuel breeding blanket technology and remote handling involving approximately 60 personnel. The future of this bilateral remains uncertain while the Canadians decide on whether and/or how to continue their future domestic activities.

- U.S.-China Bilateral: Covers physics and some technology areas at a modest level of activity of about 10 exchanges.
- U.S.-Korea Bilateral: The newest bilateral arrangement now being implemented for the first time. Provides auspices for the KBSI-PPPL contractual arrangement in support of the KSTAR project.

The Multilateral Agencies

- Under IEA auspices, there are currently eight active agreements covering a wide range of activities. One of the newest activities is a set of tasks, one addressing the technical issues arising from a recently completed conceptual design of a high flux neutron source and another a feasibility study of a high volume neutron source. Another new activity is the exploration of the current and future uses of remote access to and participation in experiments
- Under IAEA auspices, the newest activities are explorations for means to increase cooperation between programs in the North and the South and an exploration of how the IAEA and IEA can work together complementarily for fusion.